Investigation of Seismic Base Isolated Structures for Long Period Ground Motions

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Abstract— **In this research lead core rubber bearing (LCRB) seismic isolator is designed such that the available period (4secs) of it is increased to (6secs), low period important structures (hospital, school, and similar structures) equipped with this type isolator has exhibited safer behavior at least around extremum range of the strong and long period earthquake excitations and proposed for related applications. The LCRB6 seismic isolation system and the hospital building resting on isolation system has been modeled in LS-DYNA finite element software and analyzed using various strong and long period ground motions, related response results of the structure have been presented.**

***Index Terms*— base isolation, nonlinear dynamic analysis, LS-DYNA modelling, strong and long period earthquake excitations, earthquake resistant structures;**

I. Introduction

The main idea of the seismic base isolation is to decouple the superstructure from its base, the simplest seismic base isolation system is pure friction (PF) method, in this system the superstructure and the base of it is decoupled by a layer of mortar. In this case during earthquake action the superstructure slides on the base due to friction coefficient of mortar, the mechanical properties of this method could be described by coulomb friction law. But the main disadvantage of this system is lack of restoring force (when the superstructure slides, it will remain on its displaced place). In order to overcome this problem various other seismic base isolation methods have been developed and implemented in many projects in seismically active regions such as Japan, New Zealand, Turkey, USA etc. Elastomeric and sliding seismic isolation devices are most commonly used in practical area. Laminated rubber bearing (LRB), lead core rubber bearing (LCRB) are considered as elastomeric bearings. On the other hand, friction pendulum (F-P) and resilient friction base isolation (R-FBI) systems are popularly implemented sliding seismic isolator devices.

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Most of those seismic isolation devices have been produced with periods up to 4 seconds and implemented widely in seismic active regions such as Japan for various buildings. However, based on researches after 2011 Tohoku earthquake and other similar events shown that some base isolated buildings have been damaged in some extend, these researches come to a conclusion that the main reason for this failures were the lowness of the period of the isolator. It is believed that increasing of the period of isolation devices will improve the reliability of these device considerably which could allow the structures to overcome strong earthquakes with long periods.

Period independent seismic isolation systems such as friction based types, the response of structures using such systems, pure friction seismic isolation method, design of a new seismic isolation system integrated to the structure has been discussed in [1] [2] [3] references.

Period dependent seismic isolation systems, response of non-seismic isolated high rise buildings under effect of strong and long period earthquakes and vulnerability of these types structures and analysis of the response a new type seismic isolation system (SFSSI) has been studied in [4] [5] [6] [7] [3] references.

This research is dedicated on dynamic analysis of LCRB6 isolators and the hospital building resting on the seismic isolation system. Structure is modeled in LS-DYNA finite element analysis software, Time-history analysis of the model has been conducted using different type of strong and long period earthquakes such as 1999 Duzce, 1995 Kobe-KJMA and 1940 El Centro and 1995 Kobe-Takatori. Related Time history analysis results have been presented and proposed for implementation by pinpointing positive aspects of the research.

II. Model Description

A. Superstructure

The structure is a four story hospital building located in Samsun province of Turkey. The height and mass properties of the structure are provided in Table II-1

Table II-1 Mass and height properties of the structure

Stories	Height [m]	Mass [kg]
Base	0.8	414960.0
1	4.54	807216.0
2	4.00	769200.0
3	4.00	769200.0
4	4.00	769200.0
Total	16.54	3114816.0

The finite element model of the structure is as shown in the Figure II-1.

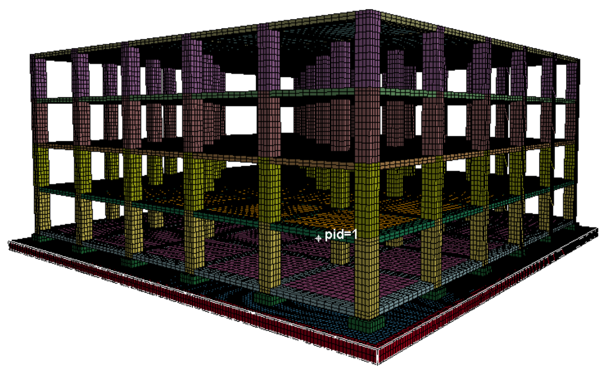

Figure II-1 3D finite element model of structure

The structure consists of five bays each 7.5 m wide, the dimension of the columns is all equally 1.0x1.0 m, the cross section of the beams has 1.0 m breadth to 0.4m depth. The height of the mat foundation is 0.8m while the dimension of the steps is 1.50x1.50x0.6m each, steps are connected with same beams as described earlier.

B. Properties of base isolation system

Generally, properties of lead core rubber isolators devices are described via component of (Wen 1976) nonlinear non-linear model. [8] Basic function of seismic base isolation can be described by a simple 2DOF system as shown in Figure II-2. Here m_b and m_s is mass of base and superstructure respectively, there are two isolators between the base and superstructure. Equation of motion for this system can written as equation (1).

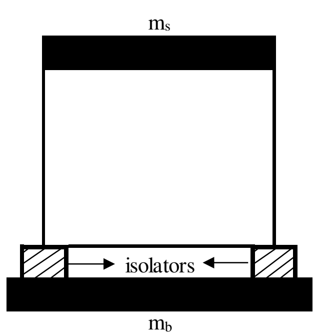

Figure II-2 2DOF base isolated model schema

$$\left[m\right]\left\{\ddot{u}\right\}+\left[c\right]\left\{\dot{u}\right\}+\left[k\right]\left\{u\right\}+\left[L\right]\left\{f_r\right\}=-\left[m\right]\left\{e\right\}\{\ddot{u}_g\} \quad (1)$$

Here {ü}, {u̇}, {u} and $\ddot{u}_g$ are acceleration, velocity, displacement and ground motion vectors respectively, {e} is location matrix for the effect of ground motion. [m], [c] and [k] can be described as following. [5]

$$M=\begin{bmatrix} m_b & 0 \\ 0 & m_s \end{bmatrix} \quad \text{(a)} \qquad C=\begin{bmatrix} c_b+c_s & -c_s \\ -c_s & c_s \end{bmatrix} \quad \text{(b)}$$

$$K=\begin{bmatrix} k_b+k_s & -k_s \\ -k_s & k_s \end{bmatrix} \quad \text{(c)}$$

Stiffness and damping of base is referred as k_b and c_b, while the superstructure's stiffness and damping is shown as k_s and c_s. In equation (1), {f_r} is the hysteretic restoring force generated by the LCRB isolator during earthquake action, [L] is the location matrix of the LCRB isolators. Based on (1976 Wen) nonlinear model {f_r} for LCRB seismic isolation device can be described as following:

$$f_r=c_b\dot{u}_b+\alpha k_b u_b+\left(1-\alpha\right)f_y Z \quad (2)$$

In equation (2), f_y refers to yield force, α stands for the ratio of post-yield to pre yield stiffness and finally Z is component of Wen's non-linear model and can be described via equation (3).

$$\dot{Z}=[Au_b-\beta\,|\dot{u}_b\,|Z\,|Z\,|^{n-1}-\tau\dot{u}_b\,|Z\,|^{n}]u_y^{-1} \quad (3)$$

Here, u_y is yield displacement can be calculated for particular structure as described in ASCE 41-13. [9]

(β, A and τ) are dimensionless components, these parameters are defined based on laboratory experiments. n is a constant value, which checks the transition from elastic to plastic behavior of the model. These equations can be solved using Newmark-Beta or 4th order Runge Kutta numerical integration methods.

a) Finite element model of isolator

A model of single isolator has been prepared as shown in Figure II-3 in LS-DYNA to study it's behaviour.

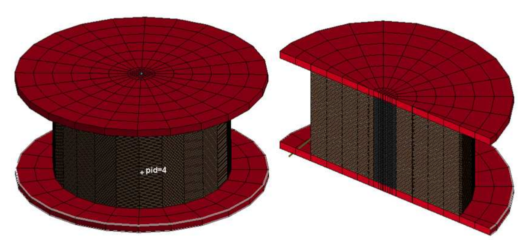

Figure II-3 Finite element model of LCRB

The model has total number of 50 rubber layers each with 4mm thickness and 49 steel shell layer with 3.1mm thickness. The total height of the isolator is 407.9mm including two flanges with 28mm thickness. The diameter of the device is 650mm while the diameter of lead core is

100mm. The material for flanges, steel plates could be defied as linear elastic or kinematic plastic, but material for rubber should be modeled using either hyperplastic or viscoelastic materials. [10]

b) Discrete beam FEM model of isolator

In large scale base isolation projects using full solid model as defied in earlier section is very uneconomic in terms of computer resources and in most cases very time consuming during analysis. Discrete beam model is an alternative method for modeling of seismic isolators, in this approach the isolator will be modeled as a discrete beam and the properties of the isolator is defined as material and assigned to the discrete beam. The isolator material is developed based on (1976 Wen) model as described earlier, the algorithm which presented by (Nagarajaiah, 1991) for the implementation of seismic isolators case were used in LS-DYNA. [11] This material can be used to model lead core rubber bearing (LCRB), friction pendulum (PF) and sliding (two perpendicular curved beams) seismic isolation systems. Vertical stiffness (K_v), yield displacement (u_y), yield force (f_y) and damping coefficient is the main parameters that is necessary in the modeling of discrete beam isolator. These parameters can be calculated based on ASCE 7-16 [12] and ASCE 41-13 [9] codes. Kv is calculated using equation (3)

$$K_V = \frac{(E_c A)}{R_T} \quad (3)$$

Where, A and R_T is area and the thickness of the elastomeric seismic isolator, and E_c is vertical elasticity modulus, E_c can be calculated using equation (4).

$$E_c = \frac{6GS^2K}{6GS^2 + K} \quad (4)$$

Here K and G is bulk and shear modulus of rubber respectively. Commonly, K=2000 MPa, and G=0.42 MPa has been used for calculation of the properties of LCRB devices.[13] S is the shape factor of elastomeric isolator, the value of S should be between 12 to 20. Yield displacement (u_y) is 0.05~0.1 time of R_T. Yield force is related to characteristic strength (Q), yield displacement, and post yielding stiffness (K_p) of the isolator, yield force is presented via equation (5).

$$F_y = Q + K_p D_y \quad (5)$$

Post yield stiffness (K_p) is mainly related to G, A, and R_T, it can be approached by equation (6).

$$K_p = \frac{GA}{R_T} \quad (6)$$

Characteristic strength of the isolator is described based on design displacement of isolator (D_D), effective damping (β_{eff}) and yield displacement via following equation.

$$Q = \frac{\pi\beta_{eff} K_p D_D^2}{(2-\pi\beta_{eff})D_D - 2D_y} \quad (7)$$

Design displacement of isolators are related to the weight, period, damping coefficient of the system. This parameter could be calculated using equation (8).

$$D_D = \frac{gS_{D1}T_D}{4\pi^2 B_D} \quad (8)$$

Here, g stands for the gravity, S_{D1} for site coefficient component, T_D design period and B_D refers to damping coefficient.

Based on above descriptions the isolator device parameters; vertical stiffness (K_v), yield displacement (u_y), yield force (f_y) has been calculated with 6sec period for this particular building. Three different types of LCRB isolator properties are used due to distribution of structural loads on the columns. The parameters of the isolators are provided in Table II-2.

Table II-2 Parameters of the isolator

Parameters	Type A	Type B	Type C
f_y [N]	6.35E+04	3.17E+04	1.59E+04
K_v [N/m]	2.67E+08	3.01E+08	1.50E+08
u_y [m]	0.016	0.016	0.016

III. Time History analysis

Time history analysis of the four story hospital structure has been conducted using 4 couple of strong earthquake time history records. The list of the earthquakes has been provided in Table III-1.

Table III-1 List of implemented earthquakes

Name	Station	Year	PGA -X	PGA -Y
Duzce	Bolu	1999	7.14	7.86
Kobe	KJMA	1995	7.88	5.6
Imperial Valley	El Centro	1940	2.75	2.00
Kobe	Takatori	1995	6.03	6.18

The unite of the acceleration is m/sec^2

A. Time history analysis results

The acceleration, velocity and displacement responses of the foundation, steps and the top story under effect of seismic ground motions mentioned in Table III-1 is presented in the following:

1) 1999 Duzce earthquake

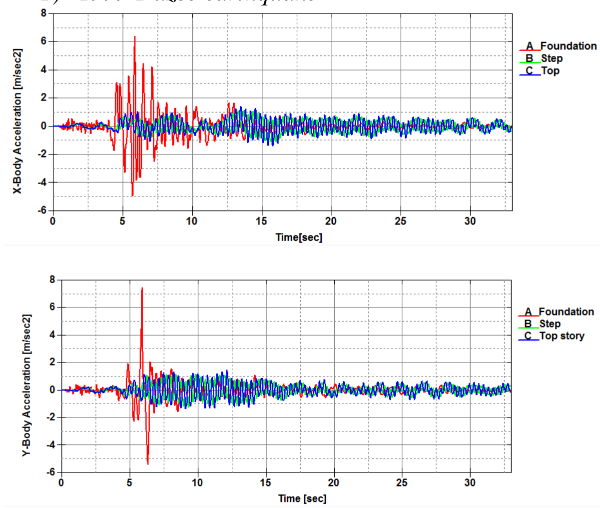

Figure III-1 Acceleration response of foundation, steps and top story due to Duzce earthquake in X and Y direction respectively.

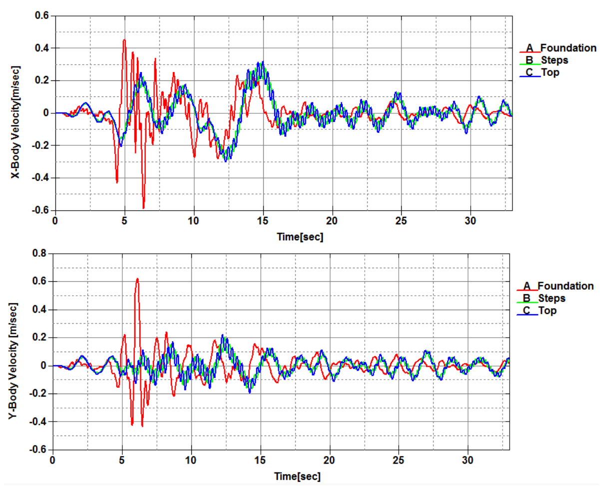

Figure III-2 Velocity response of foundation, steps and top story due to Duzce earthquake in X and Y direction respectively.

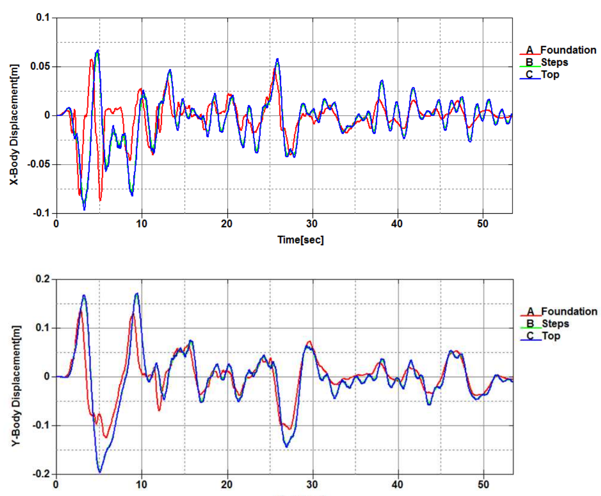

Figure III-3 Displacement response of foundation, steps and top story due to Duzce earthquake in X and Y direction respectively.

2) 1995 Kobe-KJMA Earthquake

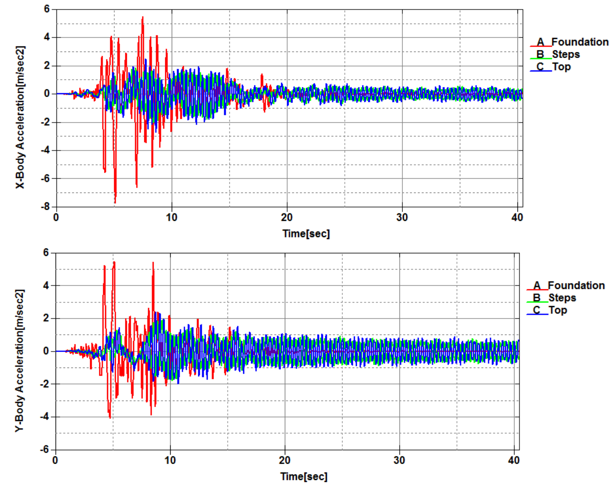

Figure III-4 Acceleration response of foundation, steps and top story due to Kobe-KJMA earthquake in X and Y direction respectively.

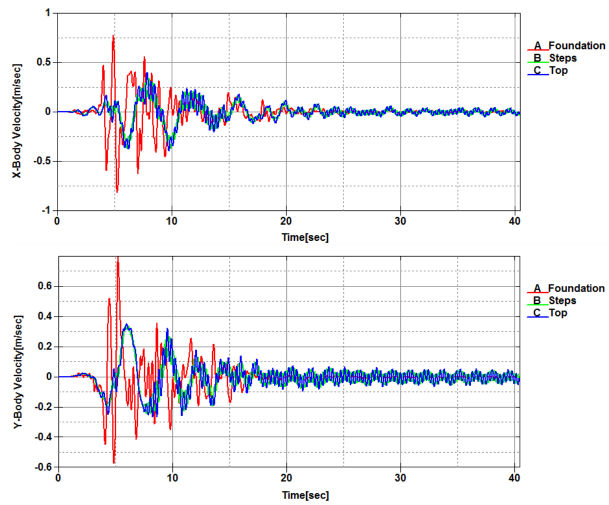

Figure III-5 Velocity response of foundation, steps and top story due to Kobe-KJMA earthquake in X and Y direction respectively.

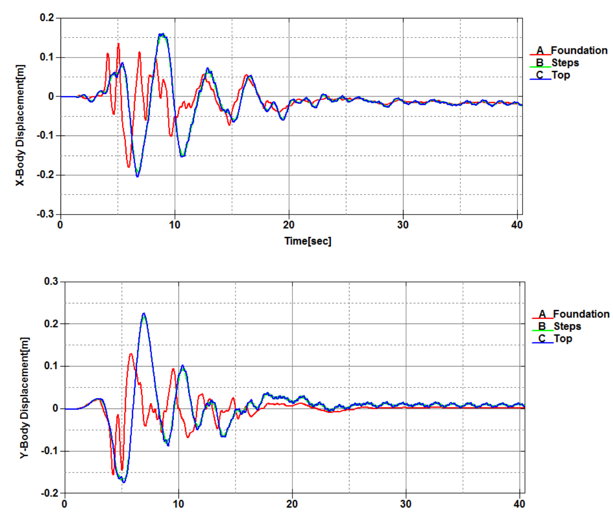

Figure III-6 Displacement response of foundation, steps and top story due to Kobe-KJMA earthquake in X and Y direction respectively.

3) 1940 El Centro earthquake

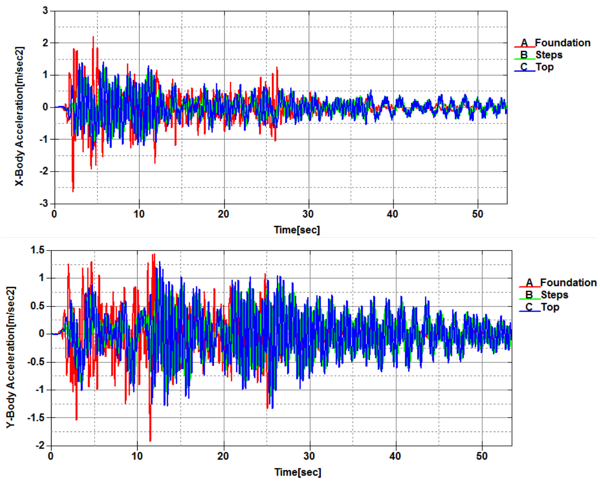

Figure III-7 Acceleration response of foundation, steps and top story due to El Centro earthquake in X and Y direction respectively.

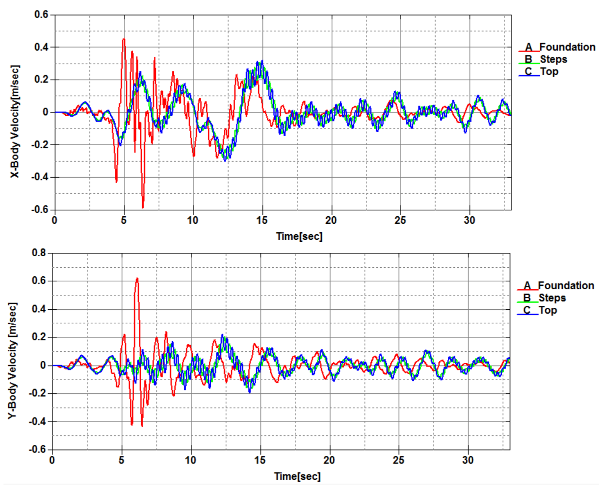

Figure III-8 Velocity response of foundation, steps and top story due to El Centro earthquake in X and Y direction respectively.

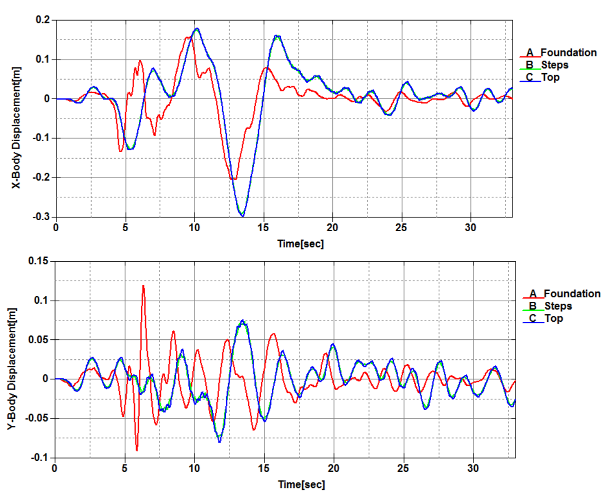

Figure III-9 Displacement response of foundation, steps and top story due to El Centro earthquake in X and Y direction respectively.

4) 1995 Kobe-Takatori Earthquake

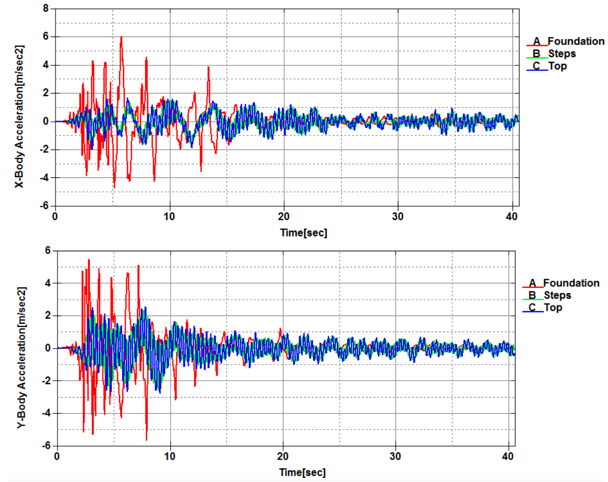

Figure III-10 Acceleration response of foundation, steps and top story due to Kobe-Takatori earthquake in X and Y direction respectively.

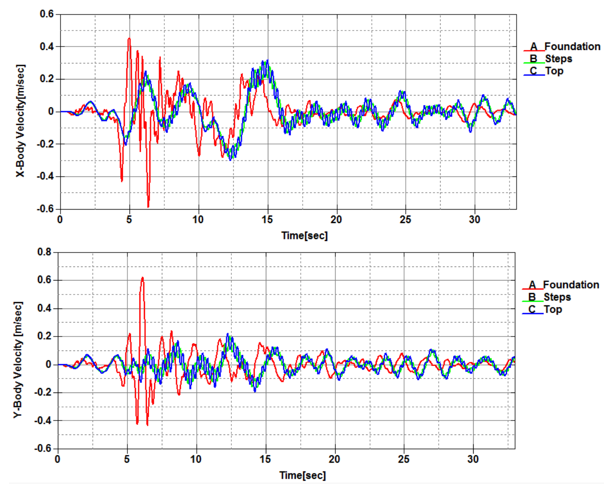

Figure III-11 Velocity response of foundation, steps and top story due to Kobe-Takatori earthquake in X and Y direction respectively.

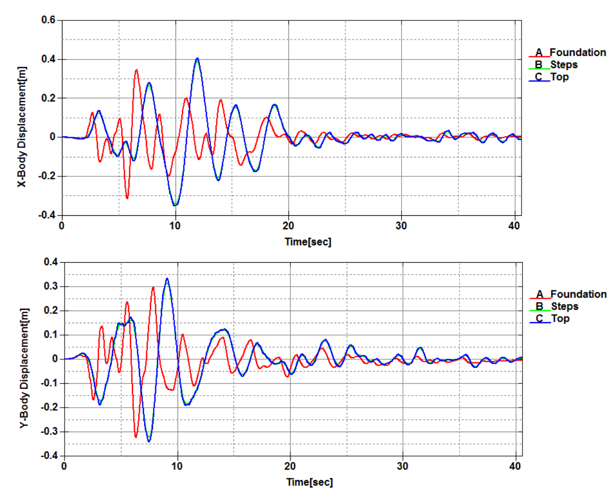

Figure III-12 Displacement response of foundation, steps and top story due to Kobe-Takatori earthquake in X and Y direction respectively.

IV. Conclusion

Time history analysis result exhibits significant reduction in acceleration response of structure compared to foundation level, as depicted in figures IV-1 and IV-2 the superstructure acceleration reduced %82, %68, 50% and %65 due to effect of Duzce, Kobe-KJMA, El Centro and Kobe-Takatori earthquakes respectively, in average there are %65.25 reduction in acceleration responses of structures in X and Y directions.

Another important aspect of analysis result is that the structure appears to have not imposed to resonance at least in the extremum impact zones of the earthquakes.

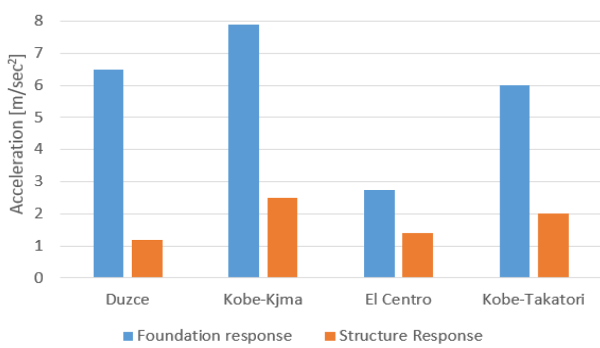

Figure IV-1 Reduction of peak acceleration response of foundation and superstructure in X-direction

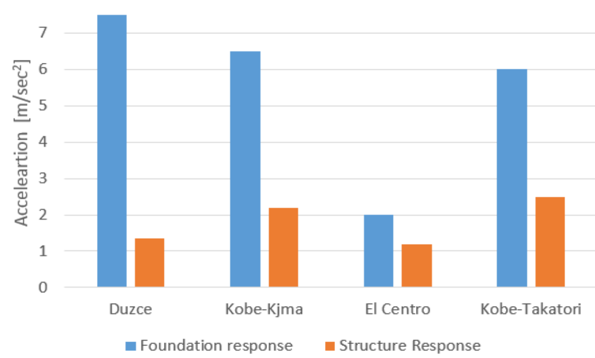

Figure IV-2 Reduction of peak acceleration response of foundation and superstructure in Y-direction

Therefore, the usage of LCRB6 isolator is effective for protection of low rise building such as hospitals, schools, museums… and shows safer behavior in peak ground motion range of the of strong and long period earthquakes, thus usage of such isolator is recommended for implementation.

V. References

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